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Measurement of fission products β decay properties using a total absorption spectrometer

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Abstract. In a nuclear reactor, the β decay of fission fragments is at the origin of decay heat and antineutrino flux. These quantities are not well known while they are very important for reactor safety and for our understanding of neutrino physics. One reason for the discrepancies observed in the estimation of the decay heat and antineutrinos flux coming from reactors could be linked with the Pandemonium effect. New measurements have been performed at the JYFL facility of Jyväskylä with a Total Absorption Spectrometer (TAS) in order to circumvent this effect. An overview of the TAS technique and first results from the 2009 measurement campaign will be presented.

1. Introduction

The β decay process is of great relevance to get an insight into the structure of exotic nuclei. An accurate determination of the β-decay intensity distribution is necessary for basic nuclear physics but also in the fields of reactor technology, astrophysics and fundamental interactions. In a reactor core, the fission process produces fission products that are mostly radioactive neutron-rich nuclei decaying via β^- decay:

$$^{A}_{Z}X \longrightarrow ^{A}_{Z+1}Y + e^- + \bar{\nu}_e$$

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At the shutdown of a reactor there is still some power generated coming essentially from β decay and subsequent γ emission. This is called the *decay heat*, and represents $\sim 7-8\%$ of the nominal power of the reactor. Therefore this residual power constitutes a key parameter for safety. One method to calculate the decay heat is based on statistical considerations [1]. With the increasing amount of the available decay data the most used calculation and the only predictive method for future reactors is now the *summation method*. This method is based on the summation of the activity of all nuclei times the mean energy released during the decay:

$$f(t) = \sum_i (\bar{E}_{\beta,i} + \bar{E}_{\gamma,i} + \bar{E}_{\alpha,i})\lambda_i N_i(t). \tag{1}$$

Where $f(t)$ is the power function, E_i the mean energy of the γ or β and α particles, λ_i is the decay constant of the i^{th} nuclide and N_i their number at time t.

Yoshida et al. have shown [2] that there are discrepancies in the decay heat calculation performed with the summation method using different databases (JEFF, JENDL and ENDF-B), compared with reference integral decay heat measurements.

β decay is also source of $\bar{\nu}_e$ in nuclear reactors. Studying the $\bar{\nu}_e$ coming from reactor is very important for understanding antineutrino physics, for instance for the determination of the θ_{13} parameter in the ν oscillation theory. Refer to [3–5] for further details. The spectrum of $\bar{\nu}_e$ depends on the nuclear structure relevant for different decays. Thus the emitted $\bar{\nu}$ flux depends in norm and shape on the fuel composition of the reactor. Hence, antineutrinos can be a useful tool for monitoring reactor core content for non proliferation. For these purposes a precise determination of antineutrino spectra is needed. The antineutrino spectrum of one fission product is the sum over the beta branches of all the antineutrino spectra of the parent nucleus to the daughter nucleus weighted by their respective branching ratio. The total $\bar{\nu}$ spectra is determined by summing over all fission product contribution with respect to the fission yield as stated in equation (2) [6, 7].

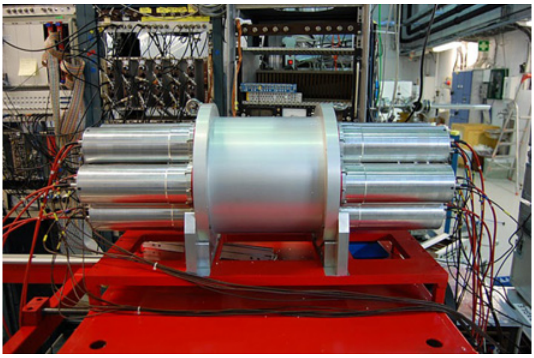
$$N_{\bar{\nu}} = \sum_i Y_i(A, Z, I, t) \sum_j b_{ij}(E_0^j) P_{\bar{\nu}}(E_{\bar{\nu}}, E_0^j, t). \tag{2}$$

Where $N_{\bar{\nu}}$ is the antineutrino spectrum, Y_i the fission yield, b_{ij} the β branching ratio and $P_{\bar{\nu}}$ the reference ν spectrum. A recent comparison of $\bar{\nu}$ spectra computed using the summation method, with reference integral data [6, 7] has shown discrepancies that could be due to some biases in the nuclear data. Indeed, branching ratios, endpoint energies and half-lives that are needed in the summation method (for decay heat or antineutrino spectrum) are all retrieved from nuclear databases.

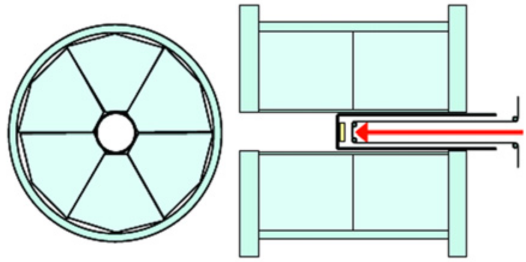
2. Total absorption spectrometer

2.1 Pandemonium effect

β decay properties are usually determined by measuring the intensity and energy of γ-rays emitted after β transition of a parent nucleus to its daughter with high resolution Ge crystals. In the case of large Q_β, or complex de-excitation pattern, it happens that some transitions are missed due to the low efficiency of Germanium detectors for high energy gammas or high multiplicity decay cascades. This leads to an overestimation of the high energy part of the β spectra and the antineutrino ones. This is called the Pandemonium effect [8]. Some of the data present in nuclear databases suffer from the distortion caused by this effect. This feature may explain the discrepancies observed by T. Yoshida et al. [2] and in $\bar{\nu}_e$ spectra [6].



(a) a picture from the $12BaF_2$ TAS



(b) GEANT4 geometry sketch of the detector with a cross-section view and a longitudinal view showing the Si detector placed at the center and the magnetic tape

Figure 1. A 12 BaF_2 Total Absorption Spectrometer.

2.2 TAS technique

A way to avoid the Pandemonium effect is to use a Total Absorption Spectrometer (TAS), this detector is a 4π calorimeter constituted of one large or segmented crystals and with the particularity of having a γ cascade detection efficiency close to 100%. A TAS is directly sensitive to the β feeding, and for this reason represents a complementary tool for single γ peak detectors in order to solve the Pandemonium problem as illustrated in [9].

A Total Absorption Spectrometer has been developed by our collaborators of IFIC Valencia and the University of Surrey [10]. It is shown in Figure 1 and consists of 12 BaF_2 optically independent crystals arranged in a cylindrical geometry of 25 cm diameter and 25 cm long. The total gamma real efficiency estimated for this setup is 80% at 5 MeV. A silicon detector was placed at the implantation point inside the TAS for tagging beta events. In 2009, an experiment has been performed with this spectrometer at the JYFL facility of Jyväskylä in Finland to take advantage of the IGISOL facility combined with the Penning traps allowing a high purity selectivity [11]. During this experiment measurement of ^{92,93}Rb, nuclei of interest for their contribution in reactors decay heat and antineutrino spectra calculations, have been performed. In the following section we will present preliminary results of the data analysis of ^{92}Rb.

3. First results

The quantity we can extract from a TAS experiment is the β feeding distribution. Since this detector is not an ideal apparatus we do not have a direct access to this distribution, we have to deduce it from our data. This is called the *inverse problem*, which links the measured data during the experiment to the real feeding distribution of the β decay.

$$d_i = \sum_j R_{i,j} f_j. \tag{3}$$

Where d_i is the measured data in the bin i, $R_{i,j}$ is the response matrix of the TAS, which contains the relation that makes a feeding in the bin j having a contribution in the bin i of data, and f_j is the real feeding to the level that corresponds to the bin j. The response matrix is obtained by using a GEANT4 simulation of the detector which is previously validated using measured known sources.

To solve the inverse problem, we use an *Expectation Maximization* algorithm based on *Bayes* theorem and combined with a χ^2 minimisation [12]. One can appreciate the use of this process on the analysis of ^{92}Rb measured data in Figure 2, where the blue curve is the reconstructed spectrum and the black one the experimental one. This reconstructed spectrum is calculated from the feeding distribution

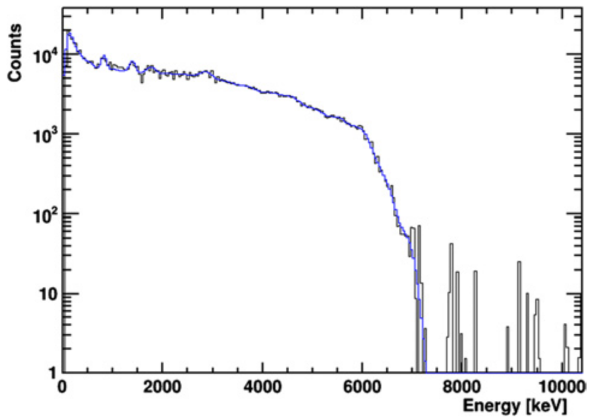


Figure 2. Superimposition of experimental spectrum (black) of the TAS and a reconstructed one (blue).

obtained by solving the inverse problem. This figure shows that we already have a good agreement between the reconstructed spectrum and the experimental one, but we are still working on the detector simulation to further improve this agreement, especially in the low energy range.

4. Conclusion

As presented in this paper, the Total Absorption Spectroscopy is a complementary technique capable to resolve the discrepancies observed in the estimation of reactor decay heat and antineutrino spectra using the summation method. We have presented here a very preliminary result from the analysis of the ^{92}Rb, nucleus measured using this technique. ^{92}Rb has been identified as a top priority nucleus that could explain the shape of the antineutrino spectra observed by the Dooble Chooz, Daya Bay and Reno experiments in the $5-6$ MeV energy range [3–5]. The analysis is on-going and the impact of this nucleus on $\bar{\nu}$ spectra and decay heat will be shortly studied.

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